

## Technical note

# Parallel path nebulizer: Critical parameters for use with microseparation techniques combined with inductively coupled plasma mass spectrometry

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## Abstract

Four different, low flow parallel path Mira Mist CE nebulizers were evaluated and compared in support of an ongoing project related to the use of microseparation techniques interfaced to inductively coupled plasma mass spectrometry for the quantification of cobalamin species (Vitamin B12). For the characterization of the different Mira Mist CE nebulizers, the nebulizer orientation as well as the effect of methanol on analytical response was the focus of the study. The position of the gas outlet on the nebulizer which consistently provided the maximum signal was when it was rotated to the 11 o'clock position when the nebulizer is viewed end-on. With this orientation the increased signal may be explained by the fact that the cone angle of the aerosol is such that the largest percentage of the aerosol is directed to the center of the spray chamber and consequently into the plasma. To characterize the nebulizer's performance, the signal response of a multielement solution containing elements with a variety of ionization potentials was used. The selection of elements with varying ionization energies and degrees of ionization was essential for a better understanding of observed increases in signal enhancement when methanol was used. Two different phenomena contribute to signal enhancement when using methanol: the first is improved transport efficiency and the second is the "carbon enhancement effect". The net result was that as much as a 30-fold increase in signal was observed for As and Mg when using a make-up solution of 20% methanol at a 15  $\mu\text{L}/\text{min}$  flow rate which is equivalent to a net volume of 3  $\mu\text{L}/\text{min}$  of pure methanol.

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## 1. Introduction

Sample introduction is considered by many to be the "Achilles' heel" of atomic spectroscopic techniques. Many of the currently available commercial sample introduction devices consisting of both nebulizers and spray chambers continue to possess limitations including poor transport efficiency, large sample consumption, nebulizer clogging and memory effect problems [1–3]. As such, several research groups have focused on improved nebulizer designs [2,4]. More recently, the focus has been on the development and characterization of a variety of low flow

nebulizers (e.g. direct injection nebulizer, DIN; high efficiency nebulizer, HEN; microconcentric nebulizer, MCN; microultrasonic nebulizer,  $\mu\text{USN}$  [4–7]. The reason for this is that low sample uptake rates (typically less than 30  $\mu\text{L}/\text{min}$ ) combined with high nebulizer gas flow rates lead to more efficient nebulization and 100% transport efficiency may even be achieved [8,9]. Using the aforementioned high efficiency low flow nebulizers, finer aerosols are produced and transported very efficiently into the plasma. The transport efficiency can be further improved by the use of organic solvents such as methanol which produces an even finer aerosol as compared to water. This phenomenon was reported by Browner et al. more than two decades ago [10,11].

Low flow nebulizers are of particular interest when interfacing capillary-based microseparation techniques to detection systems such as inductively coupled plasma mass

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spectrometry (ICP-MS). Their crucial role is to provide efficient transport of the effluents coming from the separation capillary column into the plasma. In recent studies, a low flow Mira Mist CE nebulizer was characterized and optimized for use with both capillary electrophoresis ICP-MS (CE-ICP-MS) and micro high performance liquid chromatography ICP-MS ( $\mu$ HPLC-ICP-MS) [7,12]. This parallel path nebulizer allows uptake rates in the range of 1  $\mu$ L to 2.4 mL depending on the sample solution composition. In addition, it may be used over a wide range of nebulizer gas flow rates and nebulizer clogging is not an issue due to its unique design.

The use of organic solvents in atomic spectrometry has been shown to either suppress or enhance analyte signals [10,13]. Poor measurement precision and accuracy have been reported when using organic solvents due to physical changes in the inductively coupled plasma, an increase in the number of carbon containing polyatomic ions and deposition of carbon on the sampling orifice [10,11,14–18]. However, under restricted or controlled conditions (e.g. low flow nebulizers, addition of oxygen, cooled spray chambers) the presence of organic solvents may be very beneficial in enhancing analyte signal response. Two of the most commonly cited mechanisms for this phenomenon are: (1) improvement in mass transport efficiencies and (2) increased ionization efficiency due to the so-called “carbon enhancement effect”. Increased transport efficiency has been attributed particularly to the changes in the physical properties of the sample solutions while the carbon enhancement effect has been attributed to charge transfer reactions generated by ionized carbon species or carbon containing polyatomic species. [11,19–28].

In this study, the performance of four Mira Mist CE parallel path nebulizers have been compared under optimized conditions. The orientation of the gas outlet with respect to the sample outlet was investigated. For this study, a make-up solution consisting of 20% methanol delivered at a flow rate of 15  $\mu$ L/min simultaneously with multielement analyte solutions was used. Finally, studies were conducted to try to establish if analyte signal enhancement in the presence of methanol was due primarily to improved transport efficiency or the “carbon enhancement effect”.

## 2. Experimental

### 2.1. ICP-MS instrumentation

All experiments were performed using a Perkin-Elmer Sciex Elan 6000 (Thornhill, Ontario, Canada) inductively coupled plasma mass spectrometer. The spectrometer was operated at 1 kW forward power with a coolant gas flow rate of 15 L/min and an intermediate gas flow rate of 0.86 L/min. The dwell time was 1 s. The isotopes monitored were:  $^{75}\text{As}$ ,  $^{59}\text{Co}$ ,  $^{24}\text{Mg}$ ,  $^{208}\text{Pb}$ ,  $^{103}\text{Rh}$ ,  $^{82}\text{Se}$  and  $^{89}\text{Y}$ . When changing conditions during the nebulizer characterization studies, a

10-min equilibration period was used to ensure stable operating conditions.

A routine daily performance test recommended by the manufacturer was done for the ICP-MS as a part of the optimization. Tuning procedures included continuous nebulization of two multielement solutions containing 10 ppb Mg, Cu, Rh, Cd, In, Ba, Ce, Pb and U; and 10 ppb Co, Be, In and U. For daily optimization, a syringe pump (KD Scientific Inc., New Hope, PA, USA) was operated at 30  $\mu$ L/min to introduce standard solutions through Teflon tubing attached to the nebulizer.

### 2.2. Sample introduction systems

Four Mira Mist CE parallel path nebulizers (Burgener Research Inc., Mississauga, Ontario, Canada) coupled with a cyclonic spray chamber were evaluated. For this publication, the letters A–D have been assigned to the different nebulizers. The Mira Mist CE nebulizers were operated using a 1 L/min argon nebulizer gas (controlled by the Elan's mass flow controller) at 85 psi.

To simulate microflows associated with CE, a fused silica 50  $\mu$ m i.d. capillary column (Polymicro Technologies, Inc., Phoenix, AZ) was used with a sample pumping rate of 340 nL/min and a make-up solution flow rate of 15  $\mu$ L/min. Two identical syringe pumps (KD Scientific Inc., New Hope, PA, USA) were used to control these flows. The nebulizers may be interfaced with capillary-based microseparation systems using either a tee or a four-way cross (both provide essentially the same dead volume and identical performance). In this work, a four-way cross was used. The cross provides a connection to hold the capillary column which is inserted from one side of the cross and extends all the way to the tip of nebulizer at the opposite side of the cross. The tip of the capillary column is recessed 1 mm from the tip of the nebulizer. The cross provides another port for a make-up solution which is necessary to keep the capillary column wet and it provides a fourth port to maintain the electrical connection using a platinum wire electrode for use with CE.

A 50 mL water cooled, jacketed Glass Expansion cyclonic spray chamber (Glass Expansion Pty. Ltd., Camberwell, Australia) was used to provide constant temperature. The cooled spray chamber minimizes solvent loading and provides improved precision and sensitivity. The recirculating water temperature was set to 5  $^{\circ}\text{C}$  and maintained using a Model 911 recirculating chiller from PolyScience (Niles, IL, USA). A Miniplus peristaltic pump (Gilson, France) was used to drain the waste.

### 2.3. Reagents and standards

Methanol was obtained from Fisher Scientific (Fair Lawn, NJ, USA). Stock standard solutions (High Purity Standards, Charleston, SC) were diluted with 18 M $\Omega$  deionized, distilled water to prepare two different 1 ppm

multielement standards. The first contained Co, Mg, Rh and Pb, and the second contained Co, As, Se and Y.

### 3. Results and discussion

The optimum general nebulizer operating conditions for the nebulizer have been previously described [7]. In addition, for this particular study, a setup similar to Ref. [7] was used. In summary, two multielement solutions were introduced at fixed flows of 340 nL/min through a capillary column held in place by one port of the four-way cross. The flows exiting the capillary column were combined with the make-up solution at the tip of the nebulizer. The multielement solutions were introduced through the capillary column using a syringe pump equipped with a 3 mL syringe. A make-up solution consisting of either water, 10% or 20% methanol were introduced through a different interface port using a second syringe pump equipped with a 30 mL syringe.

#### 3.1. Effect of nebulizer orientation

Initial studies focusing on Co analytical signals showed that two nebulizers of the same model (Mira Mist CE)

produced somewhat different results. Careful examination of the various details of the nebulizer design also confirmed the nebulizers were slightly different. Looking at the nebulizer end-on, the sample outlet is in the middle of the nebulizer with the capillary centered inside it. The gas outlet is in close proximity but separated from the sample outlet (see Fig. 1a). The first two nebulizers compared had the gas outlet in different positions with the first one being located at the 11 o'clock position and the second one being located at the 4 o'clock position. In addition, it was observed that the distance between the gas and sample outlet was larger for one nebulizer than for the other. These observations led us to characterize the aerosol effects in the spray chamber and the resultant impact on analytical signals by rotating the nebulizer to change the orientation of the gas outlet relative to the sample outlet.

It seems intuitive that when the aerosol cone is angled toward the center or away from the walls of the cooled cyclonic spray chamber, better transport efficiency is achieved resulting in a larger analytical signal. This is in agreement with the results presented by Todolí et al. who found decreased signal intensity when the nebulizer tip was too close to the wall of the spray chamber resulting in loss of aerosol due to impact with the spray chamber wall [29]. Shaldach et al. has also determined that the spray chamber

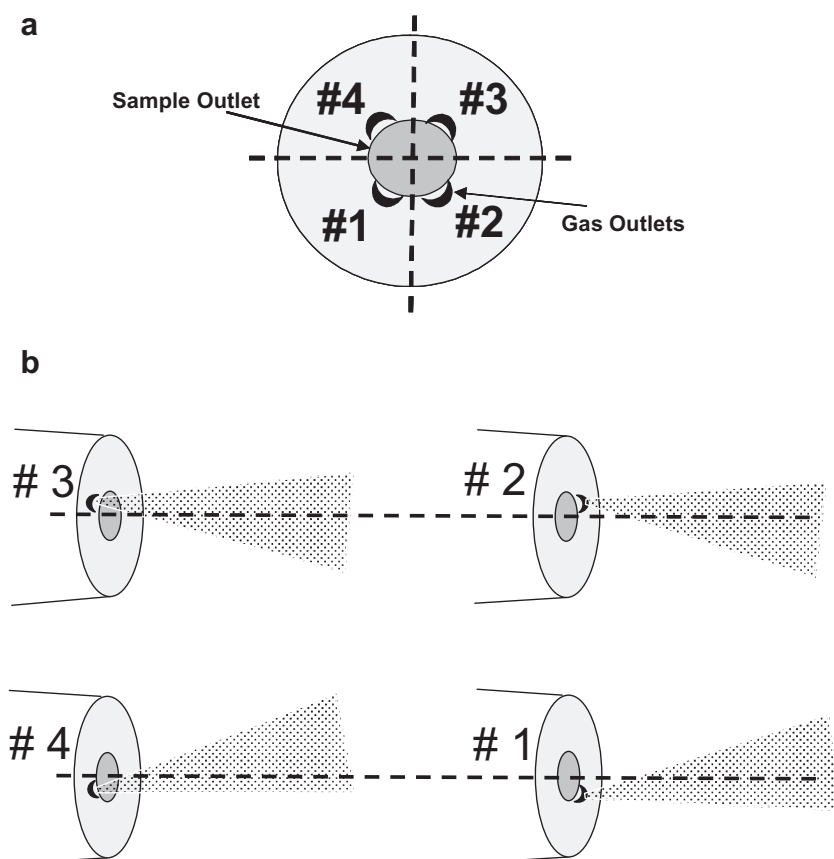


Fig. 1. Effect of gas outlet orientation. (a) End-on view of outlet tip of Mira Mist CE nebulizer showing different orientations for the gas outlet (positions 1–4). (b) Schematic representation of aerosol cone angle (top view). Number refers to gas outlet position.

geometry may be optimized to avoid collisions of aerosol with the walls of the spray chamber [30].

For this particular study, four different positions/or orientations of the gas outlet of the nebulizer with respect to the sample outlet were considered and they are illustrated in Fig. 1. Schematic representation of the front end-on view of the outlet tip of the nebulizer is shown in Fig. 1a. The different crescent shaped images illustrate the four gas outlets and are referred to as position #1 (7 o'clock), position #2 (4 o'clock), position #3 (1 o'clock) and position #4 (11 o'clock). Fig. 1b shows the top view of the four different orientations investigated and the visually observed distribution of the aerosol in the spray chamber. The horizontal dotted line was chosen as a reference point and marks the center of the sample outlet. The position numbers should be correlated with the numbers assigned in Fig. 1a.

To study the effect that nebulizer orientation had on the analytical signal, four different elements present in a 1 ppm Co, Rh, Mg and Pb multielement solution were monitored. From the results, it was observed that positioning of the gas outlet with respect to the sample outlet had a significant impact in the transport efficiencies which are represented by the magnitude of the analytical responses of the different elements. Maximum signals were observed at position #4 for all elements. The next most sensitive orientation was with the gas outlet at position #3 followed by position #1. Position #2 consistently resulted in the poorest sensitivity for nebulizer A.

The superior sensitivity observed in position #4 is directly attributable to the aerosol cone angle, as illustrated in Fig. 1b. As can be seen in this figure, at position #4 (11 o'clock) the aerosol is better directed toward the center of the spray chamber. This particular orientation increases the likelihood of having a larger percentage of aerosol reaching the plasma. At position #2 (4 o'clock) where the lowest number of counts was observed, the decreased signal is most likely the result of the aerosol impacting the spray chamber walls and being drained to waste. In studies reported by Mora et al. [3] and Cano et al. [31], it was shown that the shape of the aerosol cone angles depended on the nebulizer design. Both authors concluded that sharper cone angles provided increased aerosol velocity and signal enhancement while wider cone angles increased the probability of analyte loss due to impact with the walls of the spray chamber.

### 3.2. Comparison of different Mira Mist CE nebulizers

Initially, two parallel path nebulizers were investigated and compared (nebulizers A and B). For their comparison, Co was the only element monitored. When comparing the Co analytical signals obtained with both nebulizers it was clear that changes in gas outlet orientation and spacing have a smaller impact on nebulizer B. Position #4 still provides maximum Co signal intensity regardless of the nebulizer and whether or not methanol is used. Nebulizer A provided

twice the sensitivity that could be obtained with nebulizer B. The difference in sensitivity may be due to a difference in the interaction of the gas and liquid streams of the two nebulizers. In nebulizer A the gas outlet is closer to the sample outlet and is obviously resulting in more aerosol being formed.

Fig. 2 shows the performance of four different nebulizers of the same model. Overall, nebulizer A provided the highest signals regardless of the element being studied. More similar performance was seen for the other three nebulizers with the exception of nebulizer B which exhibited pronounced low sensitivity for Rh and Pb as compared to the other nebulizers. A possible explanation for the similarity in results between B, C and D could be related to the visually observed similarity in their designs. For each of these three nebulizers, similar distances were seen between the gas and sample outlets and that distance was greater than the distance seen for nebulizer A. Discussions with the manufacturer confirmed that all four nebulizers were manufactured in a similar manner yet because they are handmade, slight differences do exist. Based on our results, the manufacturer recommends optimizing operating conditions by systematically rotating the nebulizer to identify the orientation that provides maximum sensitivity.

### 3.3. Carbon enhancement effect

As stated previously, several research groups have shown that the addition of organic solvents to aqueous sample solutions may enhance the signal response for selected elements. Fig. 3a clearly illustrates that the presence of methanol led to enhanced signals for all different elements studied. In addition, this figure shows the effect that nebulizer orientation had on the analytical signals. Even though the increase of the magnitude of the signal is not linear when increasing the methanol concentration from 0% to 10% and 20%, the trend is similar for all elements except

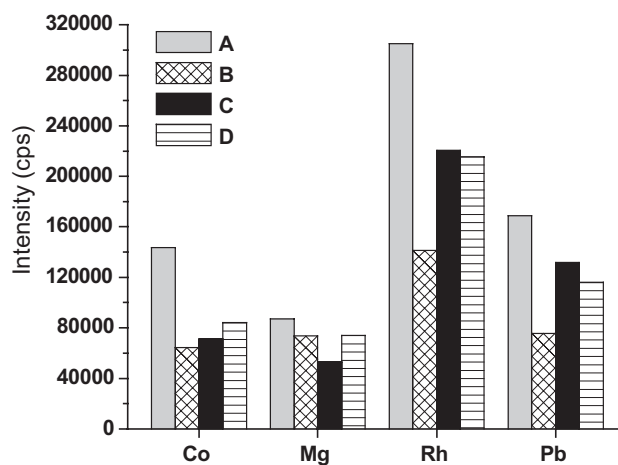


Fig. 2. Analytical performance of four Mira Mist CE nebulizers (A–D) showing data for 1 ppm Co, Mg, Rh and Pb using 15  $\mu$ L/min of 20% methanol make-up solution.

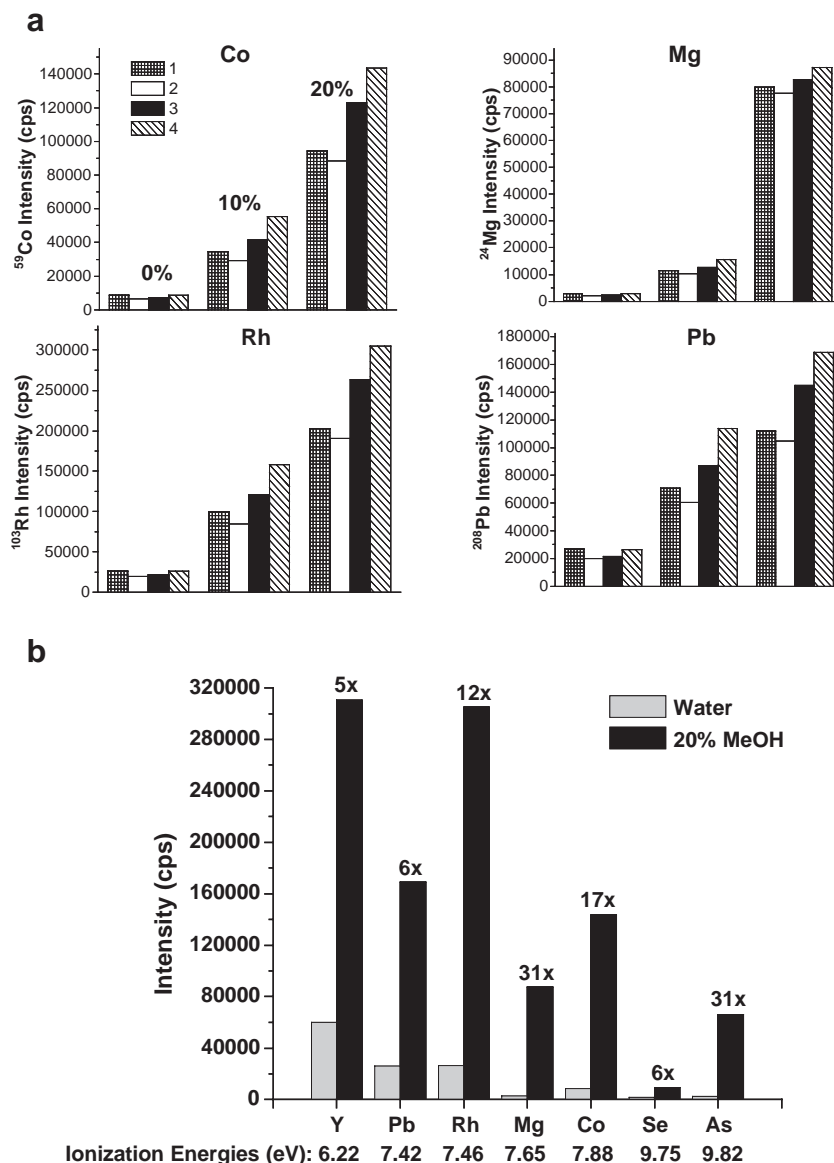


Fig. 3. Carbon enhancement effect studies. (a) Signal response for the different methanol concentrations and gas outlet orientations (positions 1–4). (b) Correlation between signal response, presence of methanol and ionization energies.

for Mg. For Mg, a drastic change in sensitivity is observed when the concentration is raised from 10% to 20%. A review of the data highlights the fact that the addition of methanol has a far greater effect on analytical response for all elements than does changing the position of the gas outlet. In the absence of methanol, the magnitude of the analytical signals (# of counts) at the different positions is virtually the same.

The proposed mechanisms in the literature related to the increased signal response when using methanol focus on improvements in transport efficiency (physical properties of organic solvents leading to the production of finer aerosols as a result of decreased surface tension and viscosity) and/or alteration of ionization processes taking place in the plasma as a result of the so-called “carbon enhancement effect”. An interesting study by Campbell et al. [20] highlighted the fact

that both processes may be expected to play a significant role; however, he concluded that physical transport processes were not likely to be the predominant cause of signal enhancement with the addition of Triton X-100 due to the fact that significantly different degrees of signal enhancement were observed for As (500%) as compared with Y, Co and In (30%) under the same transport conditions. Based on Campbell’s reported findings, combined with current data from this study, a decision was made to try to further elucidate the mechanism responsible for significant signal enhancement in the presence of organic solvents.

For this study, elements were selected based on literature reports combined with their ionization energies and expected degree of ionization [32,33]. Multiple 1 ppm multielement standards were nebulized under the same conditions (nebulizer gas flow 1 L/min; sample uptake rate



of 340 nL/min; make-up solution uptake rate 15  $\mu\text{L}/\text{min}$  using either water or 20% MeOH). All results were obtained using nebulizer A at position #4 (11 o'clock). Fig. 3b shows the analytical signals for the different elements investigated. White bars represent the absence of methanol while the black bars represent the effect of the presence of 20% methanol introduced into the plasma at a rate of 15  $\mu\text{L}/\text{min}$ . The elements are plotted in order of increasing first ionization energy values (left being the lowest). From these results, it can be seen that the elements monitored (when using pure water) are classified into two distinguishable groups: elements with ionization energies lower than 7.46 eV and elements with ionization energies higher than 7.65 eV (7.65–9.82 eV). As expected, based on the reported degrees of ionization from the literature, elements with ionization energies between 6.22 and 7.46 eV produced intensity values higher than for the other group of elements. This illustrates clearly the fact that more easily ionized elements produce larger signals.

Fig. 3b clearly shows that the presence of methanol increased the signal intensity values for all elements investigated regardless of the ionization energy. What is most notable is that large increases (factors of  $10\times$  or more) are seen for both the “easily ionized” group of elements as well as those with higher ionization energies. Overall, the largest effects are seen for As and Mg which both experienced a more than 30-fold enhancement when methanol (15  $\mu\text{L}/\text{min}$  of 20% MeOH) was added which is equivalent to a net volume of 3  $\mu\text{L}/\text{min}$  of pure MeOH. This is in contrast to predictions in the literature such as the reports by Larsen and Stürup [19] and Gammelgaard and Jøns [27] who expected to see significant enhancements only for those elements with ionization energies in the 9–11 eV range due to “chemical ionization” which can affect those elements that are not already completely ionized in a conventional argon plasma. Their explanation was that by adding organic solvents, the elements investigated were fully ionized by the generation of charge transfer reactions from ionized carbon species or carbon containing polyatomic species. The data from this study clearly highlight the fact that more than one factor is contributing to increased signal intensity when methanol is added to the make-up solution.

Signal enhancements observed with the addition of methanol are clearly due to both physical effects resulting in increased transport efficiency as well as carbon enhancement effects related to ionization energy and degree of ionization. Gammelgaard and Jøns [27] also found there was no correlation between molar concentrations of carbon and signal enhancement factors. Kralj and Veber [23] evaluated the addition of different carbon containing compounds to provide equal numbers of moles of carbon, and found that acetonitrile and methanol provided superior signal enhancement as compared with TRIS, glucose and ammonium acetate, concluding that volatility played a major role and that improved ionization efficiency does as well. In summary, although there are numerous literature reports,

further study is needed to better understand the exact mechanism(s) of enhancement resulting from the use of organic solvents. A key point is that literature reports must clearly state the exact experimental conditions used. It is pointless to say that 20% methanol was added without stating clearly what the flow rate was because it is important to be able to calculate the number of moles of carbon in the plasma to compare it to the amount of analyte of interest. Likewise, it is important to present details related to the sample introduction system including information about the type of nebulizer as well as the features of the spray chamber including the geometry and whether or not it is cooled.

#### 4. Conclusions

The analytical performance of four Mira Mist CE parallel path nebulizers combined with a water cooled jacketed cyclonic spray chamber have been compared. The first nebulizer was purchased in 2001 and the last three were provided by Burgener Research, Inc. for us to evaluate in 2003. The analyte signals achieved for the three newest nebulizers demonstrated that although they are manufactured by hand, equivalent sensitivities may be obtained with optimization by rotating the nebulizer to position the gas outlet in the same location. In this study, it was found that the orientation of the gas outlet with respect to the sample outlet played a critical role in the magnitude of analytical signal response because it determined the aerosol cone angle. Optimum analytical signals were observed when the aerosol was directed toward the center of the spray chamber, avoiding impact with the walls of the cyclonic spray chamber with position #4 (gas outlet at 11 o'clock) providing maximum sensitivity. Signal enhancement (as much as 30-fold for Mg and As) was observed for all elements studied when 20% methanol was introduced into the makeup solution at a rate of 15  $\mu\text{L}/\text{min}$ . Even though transport efficiency and carbon enhancement effect both may contribute to enhanced analytical signals when adding organic solvents to aqueous sample solutions, it seems that the later effect could be the dominant contributor to signal enhancement.

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